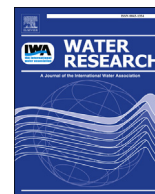


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Review

Resilience theory incorporated into urban wastewater systems management. State of the art

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ABSTRACT

Government bodies, utilities, practitioners, and researchers have growing interest in the incorporation of resilience into wastewater management. Since resilience is a multidisciplinary term, it is important to review what has been achieved in the wastewater sector, and describe the future research directions for the forthcoming years. This work presents a critical review of studies that deal with resilience in the wastewater treatment sector, with a special focus on understanding how they addressed the key elements for assessing resilience, such as stressors, system properties, metrics and interventions to increase resilience. The results showed that only 17 peer-reviewed papers and 6 relevant reports, a small subset of the work in wastewater research, directly addressed resilience. The lack of consensus in the definition of resilience, and the elements of a resilience assessment, is hindering the implementation of resilience in wastewater management. To date, no framework for resilience assessment is complete, comprehensive or directly applicable to practitioners; current examples are lacking key elements (e.g. a comprehensive study of stressors, properties and metrics, examples of cases study, ability to benchmark interventions or connectivity with broader frameworks). Furthermore, resilience is seen as an additional cost or extra effort, instead of a means to overcome project uncertainty that could unlock new opportunities for investment.

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1. Introduction

Recent debates place resilience at the core of sustainability thinking, as systems need to become resilient to overcome future uncertainty (Moddemeyer, 2015), with the ambition that resilience is considered a boundary concept in sustainability research (Olsson et al., 2015). The concept originated from the field of ecology (Folke, 2006) but the engineering sector is reshaping and incorporating it into the planning and design of urban infrastructure.

The concept of resilience in urban water management is gaining momentum in both academia and industry, drawing attention from international conferences and top level organisations (e.g. Amsterdam International Water Week (AIWW) 2015, Water Environment Federation Technical Exhibition and Conference (WEFTEC) 2015, Water Environment Research Foundation (WERF) (Gay and Sinha, 2013), and the International Water Association (IWA) water wise cities initiative). Other initiatives include the “100 resilient cities” project, pioneered by the Rockefeller Foundation (100RC, 2013), which gives expert support to cities around the world to become more resilient. The main reason for this momentum is that wastewater infrastructure has traditionally been designed to provide collection and treatment services, supporting human health and environmental protection. Now, planning has to account for the extremes of climate change which impacts on the flow to treatment and the receiving water.

The research sector is moving to support these initiatives, albeit slowly in comparison with the increasing demand of industry and government. However, there is no clear roadmap on how water research can contribute. Hence, the aim of this paper is to critically analyse the state of the art in resilience assessment as applied to wastewater systems management and to define future research directions that contribute to operationalizing its implementation.

This paper is structured as follows: firstly, the background of resilience theory is presented briefly, describing the evolution of the concept over time with contributions from related fields (i.e. social-ecological and engineering fields). Secondly, a summary of key studies is presented, followed by an analysis of: stressors, properties, metrics and interventions to increase resilience. Finally, important future research directions in the field are identified.

2. Resilience background

The resilience concept originated from the ecology field in the 1970s, where resilience was understood as the capacity of an ecosystem to survive, adapt, and grow in the face of unforeseen changes (Holling, 1973). A resilient ecosystem can stay within the stable state when facing a stressor, or can adapt and enter a new stable state – i.e. change the structure while maintaining its functionality – which guarantees its existence (Fig. 1, Images 1–3). This perspective is the result of using models to monitor and manage ecosystems changes. As it gained acceptance, it started to influence other fields (Folke, 2006). Today, interdisciplinary discourse on resilience includes consideration of the interactions of

humans and ecosystems via socio-ecological systems. Resilience is defined in the social-ecological systems field as: “the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks” (Walker et al., 2004).

The engineering sector has built on this early work, especially since Holling’s (1996) seminal work: “engineering resilience versus ecological resilience”. Engineering systems are designed to provide specified services and should be efficient, continuously working and predictable (Holling, 1996). Following a perturbation, service provision should ideally remain unaltered: therefore, entering a new steady state, as might occur in a natural ecosystem, is unacceptable, and human intervention is required to return the system to the original steady state (as illustrated in Fig. 1, Images 4. a-b). A key insight gained from the social-ecological field, was the idea that resilience should consider disturbances as an opportunity to re-organize and adapt to change.

2.1. Key resilience concepts in engineered systems

An engineered system is a combination of components that work in synergy to collectively perform a useful function. Such a system can be represented as a set of variables, with a particular structure and relationship. Fig. 2 illustrates the authors’ conceptual representation of an engineering system within a resilience assessment framework. There are four elements that need to be defined in order to understand how resilience is understood within engineered systems: stressors, properties, metrics and interventions.

A stressor can be defined as a pressure on the system caused by human activities (such as increase of pollution) or by natural events (such as occurrence of a drought), and is synonymous with other terms used in resilience literature such as threat, hazard and perturbation. These stressors affect the variables of the system and in turn, the system performance. Whereas chronic stressors are well-known, recurrent and can often be estimated (e.g. urbanization and ageing of infrastructure), acute stressors are unpredictable, uncommon, and can have devastating consequences (e.g. floods, earthquakes, disease outbreaks and terrorist attacks).

Resilient engineered systems may possess several properties that allow them to withstand, respond to, and adapt more readily to stressors, for example: robustness, redundancy, resourcefulness and flexibility. These properties may be considered indicators of resilience (e.g. Yazdani et al., 2011) and have to be quantified either qualitatively or quantitatively through metrics. Further metrics used in resilience assessments, such as recovery time and failure magnitude, relate to the required performance or level of service of the system. Note the distinction between properties and performance: whilst both may be quantified by metrics, the ultimate goal of resilience-based design focuses on achieving the required performance. This may be provided by certain properties assumed to provide resilience, but the effects of a given system property on performance are not certain without detailed analysis (Butler et al.,

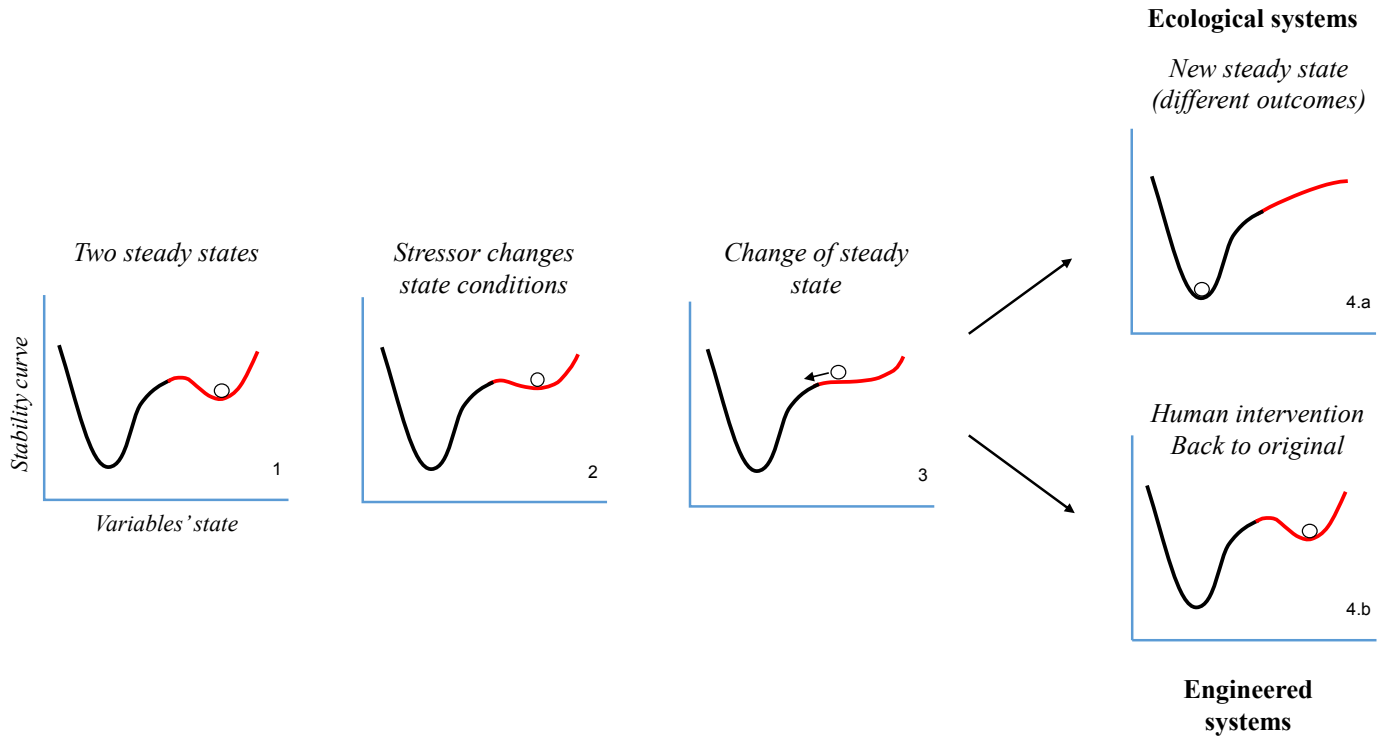


Fig. 1. Difference between ecological and engineering systems. Adapted from Holling (1996).

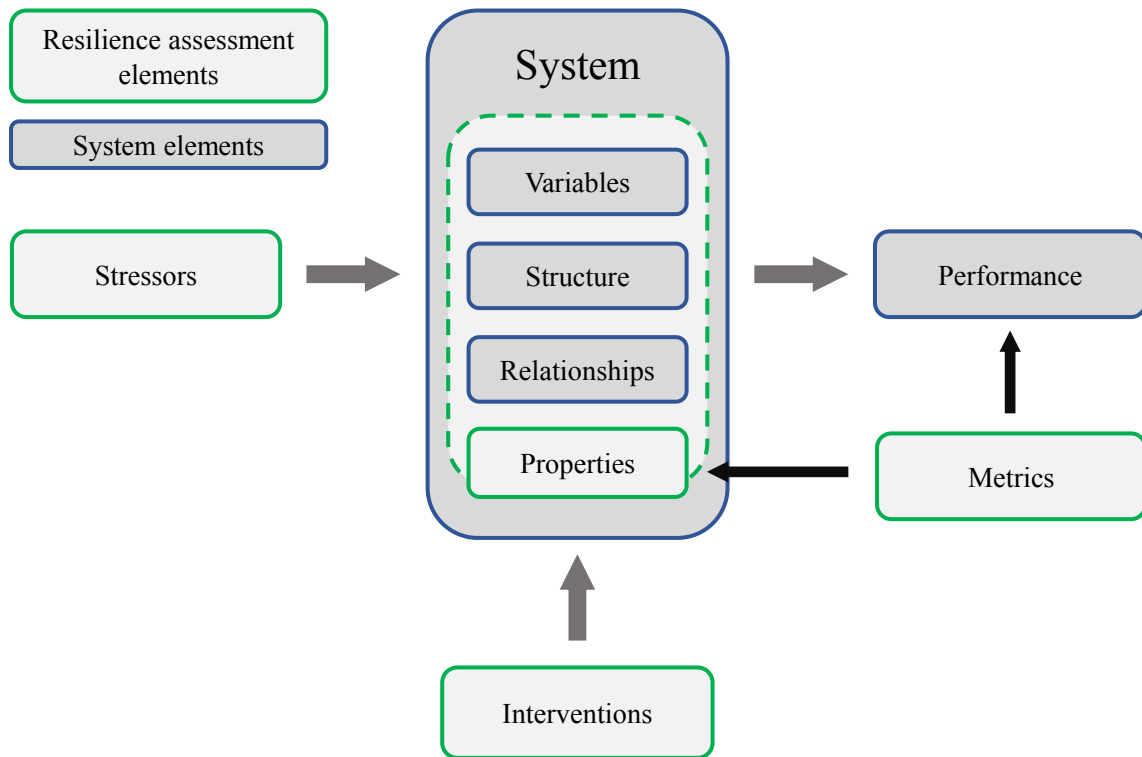


Fig. 2. Conceptual scheme of system resilience key concepts.

2016). The performance of an engineered system with respect to resilience can be improved by means of interventions which alter its properties, such as installation of spare equipment, introduction of real-time control, or increasing of system capacities.

Recent work on resilience in engineering systems includes Hosseini et al. (2016), whose review on assessment studies provides two lessons that can be inferred: (1) metrics to measure resilience are limited without a framework to guide their

implementation; (2) urban infrastructure systems are connected and influence each other. Furthermore, a recently published framework (Tran et al., 2017) aims to consider, not only the ability of the system to absorb and recover, but also to adapt over time. To do this, they have to consider the evolution of the assets and the stressors over their entire life. The resilience definition adopted is: “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events”.

Our review is concerned with the implementation of resilience in wastewater engineering as a means to enhance wastewater infrastructure management. The literature review and the analysis carried in this study have been structured following the logic shown in Fig. 2, considering each of the four elements of a resilience assessment.

3. Literature review

Resilience is a multidisciplinary term. A SCOPUS search for “Resilience” in title, abstract and keyword produced a total of 48915 articles. Including “AND water*”, the number goes down to 4702 articles. If we also include “AND Infrastructure”, only 363 articles appear. Yet, most papers still focus on ecology or non-infrastructure related issues, and the term ‘resilience’ is frequently misused in engineering studies. Our literature review was carried out using SCOPUS and the keywords: 1) Wastewater OR Sewage OR Sewer AND Resilience (289 results); title, keywords and abstract were all considered. Relevant references from the selected papers were also considered. A classification of the main characteristics of all studies considered is presented in Table 1. After manual filtering, only 17 papers were found that could be branded as “resilience assessment”; that is, those who directly applied resilience theory in wastewater management.

To complement the literature, 6 technical reports have been included from the following organisations: Water Infrastructure Asset Management Primer from WERF (Gay and Sinha, 2013) with collaboration of the IWA. Ofwat, the economic regulator of the water sector in England and Wales (Ofwat, 2015a) and UK Water Industry Research (UKWIR) (Conroy et al., 2013). Proceedings from the AIWW 2015 and the WEFTEC 2015 have also been considered.

A graphical overview of the results is presented in Fig. 3. Since the number of studies is limited, it is impossible to extract sound conclusions from statistical data. In terms of organisation type, almost half the studies belong to academia, and the other half to government and industrial organisations (Fig. 3a); only Currie et al. (2014), Xue et al. (2015) and Schoen et al. (2015) involve collaboration between academia, industry and government organisations. The scope of the studies, (Fig. 3b) includes reactors, urban drainage systems, water resource recovery facilities (WRRF) - formerly known as wastewater treatment plants - and urban wastewater systems, being the last one the most common. The assessments are usually oriented to chronic stressors (Fig. 3c), although general frameworks such as Butler et al. (2016, 2014) were considered to target both chronic and acute stressors. Finally, there is an equal mix of qualitative and quantitative assessments, with a bias towards qualitative assessment being developed by industry, and quantitative algorithms by academia (Fig. 3d). The studies have been classified in the following categories: those that propose frameworks/guidelines for water infrastructure asset management, and those that provide quantification methodologies.

3.1. Studies that propose frameworks/guidelines for water infrastructure asset management

Academia. A total of 8 academic studies present a framework or guideline towards one or more resilience key elements (stressors,

properties, metrics and interventions). Firstly, stressors have to be correctly defined, as stated by Cuppens et al. (2012). In their framework, resilience is proposed as a performance indicator for wastewater treatment, and a methodology for stressor identification is introduced, oriented to realistic modelling.

The second element is a definition for the system properties required to provide resilient performance, which is key to obtain a holistic assessment. This is also the one that requires the most effort from all the stakeholders to attain consensus. In this respect, Butler et al. (2014) present a conceptual framework for urban water management which incorporates resilience as a main tool and discusses the qualities of a resilient system. A contribution is the classification of resilience as general or specific. General resilience refers to resilience assessment against any (all) stressors, and specific refers to assessment against a set of particular stressors. This framework is further developed in Butler et al. (2016), where four different types of analysis are described: “top-down,” “bottom-up,” “middle based” and “circular”. The framework also emphasises the difference between resilience and sustainability, and clarifies the relationship between properties of a resilient system and its performance.

Thirdly, metrics need to be established that quantify system performance, linked to system properties. Although there is no specific study on metrics for the wastewater sector, a comprehensive proposal can be found in Francis and Bekera (2014), which also includes stakeholder engagement and uncertainty assessment aspects. This framework is applicable to the assessment of resilience in wastewater sewer networks as demonstrated in Mugume et al. (2014, 2015). Sweetapple et al. (2016) also present a framework on resilience assessment, with a focus on the interplay between reliability, robustness and resilience in the context of control. In this framework resilience accounts only for chronic stressors, and robustness is measured independently to account for performance under acute stressors. The study uses multiobjective analysis to assess these properties, and concludes that strategies that focus on reducing greenhouse gas emissions, may compromise total nitrogen concentration in the effluent under acute stressors.

The last key point in resilience assessment is a guidance for benchmarking interventions used to increase resilience. No framework has addressed how to decide which interventions should be benchmarked, and which properties should be considered on each case.

Resilience is also incorporated within scenario planning for wastewater treatment in Scott et al. (2012) and Gersonius et al. (2013). The first is a pioneer in resilience theory, as it presents a measure (scenario planning) for better wastewater management within the context of resilience; the definition used is “the ability to gracefully degrade and subsequently recover from a potentially catastrophic disturbance that is internal or external in origin”, considering two properties: robustness and rapidity, and including reliability measurement. The second introduces Real In Option (RIO) analysis (a technique to handle uncertainties in infrastructure at managerial level) as a method to identify an optimal set of adaptive strategies to increase resilience to climate change. Lastly, Xue et al. (2015), places resilience as a key component in the evaluation of system sustainability and highlights the lack of standardization of resilience metrics.

Industry and government. Resilience concepts are well embedded into infrastructure asset management as frameworks developed by industry and government bodies. The first example is the NYC Mayor’s Office of Recovery and Resiliency (2013), which originated after the devastating effects of Hurricane Sandy. It includes the lessons learnt after the event with a specific section on water and wastewater. Another example is the comprehensive guide to water infrastructure management developed by WEF/IWA, which

Table 1
Classification of the main characteristics of the literature branded as resilience in wastewater treatment research.

Authors	Resilience definition	Properties of a resilient system	Stressors	Scale ^a	Methodology and Scenarios ^b	Resilience measurement: metrics & equations ^c
Scott et al., 2012	Resilience is the ability to gracefully degrade and subsequently recover from a potentially catastrophic disturbance that is internal or external in origin	None specified	Chronic: changing urban density, layout, water use/ reuse; ageing of infrastructure, public perceptions	UWWS	Frame. (Qual.)/ Yes	None specified
Butler et al., 2014	Degree to which the system minimises level of service failure magnitude and duration over its design live when subject to exceptional conditions	Branded as characteristics: Redundant, Connected, Flexible Branded as attributes: Homeostasis, Omnivory, High flux, Flatness, Buffering, Redundancy	Chronic	UWWS	Frame.(Qual.)/ No	None specified
Butler et al., 2016	Degree to which the system minimises level of service failure magnitude and duration over its design live when subject to exceptional conditions	None specified	Chronic; acute	UWWS	Frame.(Qual.)/ No	None specified
Sweetapple et al., 2016	Degree to which the system minimizes level of service failure magnitude and duration over its design life when subject to exceptional conditions	Robustness, rapidity	Chronic; acute	WwTS	Frame. (Quant.)/No	Yes, robustness and recovery depends on both system performance and time.
Cuppens et al., 2012	Reduced failure probabilities, reduced consequences, reduced time to recover	Robustness, rapidity, redundancy and resourcefulness	Chronic: Storm-water Influent variations	WwTS	Frame. (Qual.)/ No	No, the focus of the paper is on definition of realistic stressors for resilience assessment
Currie et al., 2014	Degree to which the asset base can perform and maintain its desired function under both, routine and unexpected circumstances	None specified	Chronic: Climate variability and equipment failures	WwTS	Quant./Yes	Yes, performance of the treatment process and availability of the associated critical equipment.
Francis and Bekera, 2014	Ability to reduce the magnitude and/or duration of disruptive events	Absorptive, Adaptive, Recovery	Chronic: Equipment malfunction	WwTS	Frame.(Quant.)/ Yes	Yes, accounts for speed to recovery and performance measured as functionality in time
Gersonius et al., 2013	None specified	Flexibility	Chronic Climate change, flood risk	UDS	Frame. (Qual.)/ Yes	None specified
Hopkins et al., 2001	Degree to which the process can handle short-term stressors that affect the dynamics of the process	Flexibility	Chronic	ASR	Quant./No	None specified
Hwang et al., 2014	Resilience is a function of the system functionality loss and the failure event duration	Robustness, Rapidity	Chronic: Urban expansion, population growth	WwTS	Quant./Yes	Yes, it accounts for functionality loss and event duration (time)
Mabrouk et al., 2010	Speed with which the reactor recovers following a perturbation.	Recovery	Chronic	ASR	Quant./Yes	Yes, it accounts for time to return to equilibrium of control variables
Mugume et al., 2014	Ability of the UDS system to minimize the magnitude and duration of flooding resulting from extreme rainfall events.	Robustness, Rapidity	Acute: Flood risk	UDS	Quant./Yes	Yes, robustness and recovery depend on both system performance and time.
Mugume et al., 2015	Ability to maintain its basic structure and patterns of behaviour through absorbing shocks or stressors under dynamic conditions	Robustness, Rapidity	Acute: Flood risk	UDS	Quant./Yes	Yes, robustness and recovery depend on both system performance and time
Ning et al., 2013	Ability to recover from or to resist being affected by external shocks, impacts or stressors	Absorptive, Adaptive, Recovery	Chronic: Urban expansion, Runoff, Flow, Compliance	UWWS	Quant./Yes	Yes, it accounts for pollutant thresholds in the environment of a control variable.
Schoen et al., 2015	Ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions	Robustness, Adaptive, Rapidity, and Resourcefulness	Acute events	UWWS	Quant. & Qual./ Yes	Yes, it accounts for the failure profile and time duration until recovery, measured as a control variable
Weirich et al., 2015	Ability to recover from process upsets	Absorptive, Adaptive, Recovery	Chronic: Decentralization	UWWS	Quant./Yes	Yes, cost function to evaluate the performance of a control strategy for shock recovery
Xue et al., 2015	The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions To adapt our city to the impacts of climate change and to seek to ensure that, when	Robustness, Rapidity None specified	Chronic: Nutrients removal, compliance Chronic and Acute: Catastrophes	UWWS UWWS	Frame. (Qual.)/ No Frame.(Qual.)/ No	None specified None specified

(continued on next page)

Table 1 (continued)

Authors	Resilience definition	Properties of a resilient system	Stressors	Scale ^a	Methodology and Scenarios ^b	Resilience measurement: metrics & equations ^c
NYC Mayor's Office of Recovery and Resiliency, 2013	nature overwhelms our defenses from time to time, we are able to recover more quickly					
WERF foundation report: Water Infrastructure Asset Management Primer	Resilience is the ability to recover from disruption	Robustness, Redundancy, Rapidity, and Resourcefulness	Chronic and Acute	UWWS	Frame.(Qual.)/ Yes	None specified
Resilience Task and Finish Group, Ofwat, 2015a	Resilience is the ability to cope with, and recover from, disruption, and anticipate trends and variability in order to maintain services for people and protect the natural environment now and in the future	Robustness, redundancy, resourcefulness, response, recovery	Chronic	UWWS	Frame.(Qual.)/ No	None specified
Towards resilience: how we will embed resilience in our work, Ofwat, 2015b	Resilience is the ability to cope with, and recover from, disruption, and anticipate trends and variability in order to maintain services for people and protect the natural environment, now and in the future	Robustness, redundancy, resourcefulness, response, recovery	Chronic	UWWS	Frame.(Qual.)/ Yes	None specified
UK Water Industry Research (UKWIR)	Resilience is the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event	Resistance, Reliability, redundancy, Response and recovery	Chronic	UWWS	Frame.(Qual.)/ Yes	None specified
UK Water Industry Research (UKWIR)	Resilience is the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event	Resistance, Reliability, redundancy, Response and recovery	Chronic	UWWS	Frame.(Qual.)/ Yes	None specified

^a Urban wastewater system: UWWS; Urban drainage systems: UDS; Water & Wastewater Treatment Works: WwTW; Activated Sludge Reactor: ASR.

^b (Type of model/Scenario analysis). Type of model: Qualitative (Qual.), Conceptual Framework (Frame.), Quantitative (Quant.), Scenario analysis included: Yes/No.

^c Includes equation: (Yes/No); Description of measurement.

briefly introduces resiliency concepts, qualities and metrics (Gay and Sinha, 2013). In this case resilience is simply defined as the ability to recover from disruption, and four properties are considered: Robustness, Redundancy, Resourcefulness and Rapidity. The guide stays at a general level and does not provide sufficient details for practical implementation; it also recognizes the need for future resilience implementation in the water sector and the integration within broader infrastructure management frameworks. The water economic regulator in the UK (Ofwat) produced two reports to incorporate resilience assessment, Ofwat (2015a, 2015b). These two reports aim to set the role of resilience in wastewater, explain how service providers can implement it in their systems, and how to assess resilience and regulate it, from the point of view of the providers and the regulator. Complementary, the UKWIR foundation has produced two reports (Conroy et al., 2013; Conroy and De Rosa, 2013) presenting a set of Resilience Planning Guidelines intended to help introduce good practice concepts and approach to support development of water company business plans through resilience planning. These guidelines define resilience as the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event, and defines five properties: Resistance, Reliability, Redundancy, Response and Recovery.

3.2. Studies that propose quantification methodologies

A total of 9 studies were found that focused on quantification methodologies for assessment of resilience to various stressors. These studies are commonly used in optioneering projects for wastewater service options in urban planning. Ning et al. (2013), investigate wastewater infrastructure resilience to long-term changes (e.g. urban expansion and massive population movements). To this end, a grid-based database is used to build a map of land-use that estimates the impact over the years that this stressors will have on infrastructure systems. The study highlights the trade-

off between infrastructure capacity, environment needs and urban expansion; and suggests that governance and infrastructure resilience must be taken into account in urban planning. On a different line, three works have contributed to the study of performance of centralized versus decentralized wastewater systems. Weirich et al. (2015), presents a tool to predict resilience using probabilistic modelling. A 41 month data-base of effluent violations of BOD, TSS and ammonia in 211 WRRF is used to calibrate the model, which is then used to predict the effects of decentralized systems. Although the results are not conclusive, the study contributes to the resilience tools stockpile with an approach that uses time-series to predict current resilience levels at large scale, and can be complemented with other modelling approaches. Similarly, Hwang et al. (2014) investigates the resilience of a regional water supply system through a criticality analysis of five water supply components, of which wastewater reuse is analysed under two design conditions: (1) centralized versus decentralized wastewater treatment, and (2) decentralized wastewater plant location. Schoen et al. (2015) on the other hand, carry out a technological resilience assessment that includes centralized/decentralized wastewater systems and centralized drinking water systems with water reuse scenarios. In this case, four system properties and performance measures assumed indicative of resilience were reviewed under a range of acute stressors such as extreme weather and wildfire. It is important to note that no 'best' system was identified due to key uncertainties in the study.

Another use for resilience assessment is in *design studies*, using resilience and its qualities as a criteria. Mabrouk et al. (2010) calculate reactor resilience considering time to recovery -instead of effluent limit restrictions- using influent variations as a stressor. It concludes that a reactor design that maximizes productivity may not be optimal in terms of resilience. A similar study is carried in Hopkins et al. (2001), focusing only on flexibility analysis, defined as the degree to which the process can handle long-term changes to

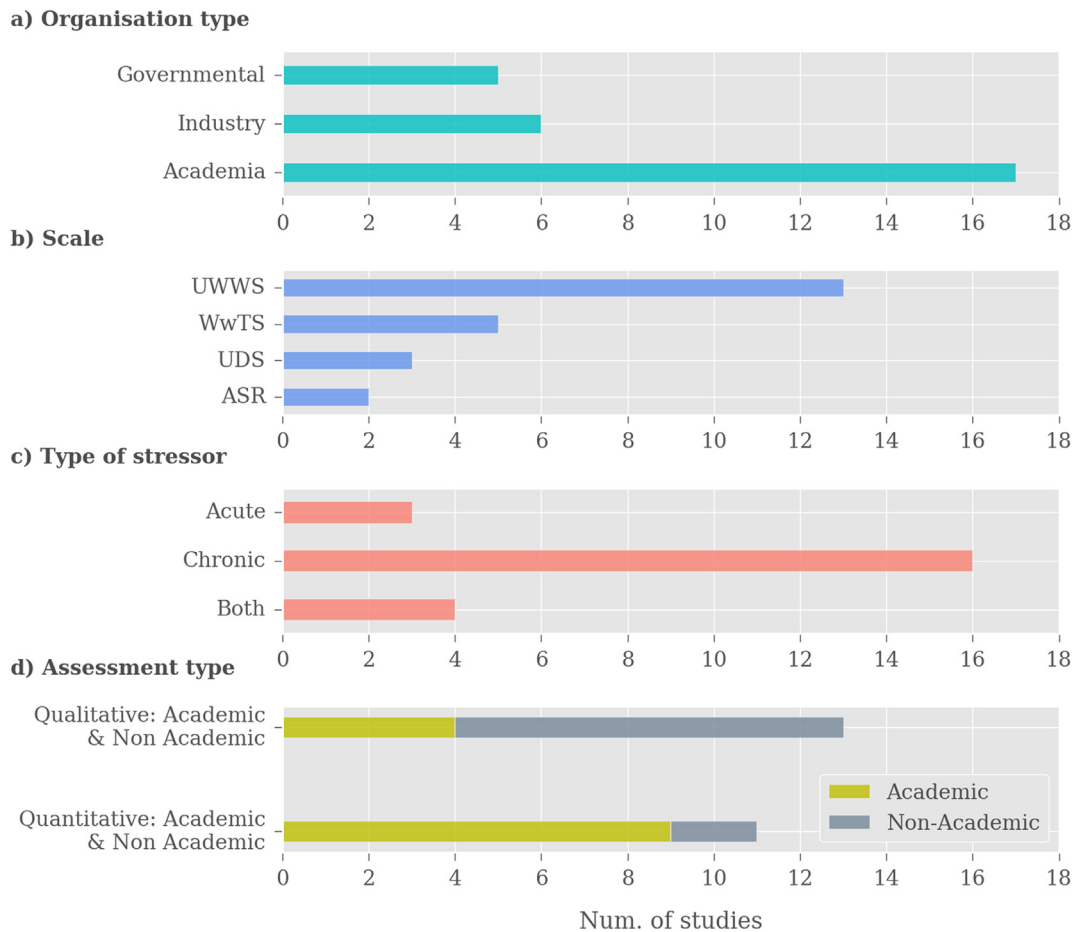


Fig. 3. Literature review overview: a) the number of times each organisation was present in the literature; b) scope of the study: urban wastewater system (UWWS), wastewater treatment system (WwTS), urban drainage system (UDS), and activated sludge reactor (ASR); c) type of stressors considered; d) the yellow line represents exclusively academic studies, the grey line non-exclusively academic studies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the steady state. This study develops a flexibility index that can be used to design resilient wastewater treatment. Resilience is also used in *asset maintenance* studies. It can be used as a means of assessing investment decisions, operational and maintenance planning to optimize budget. This is the case of [Currie et al. \(2014\)](#) in water treatment systems, which builds a reliability study on random component failures, considering actual failure rates with chronic stressors in all components. A complementary case for an acute stressor can be found in [Mugume et al. \(2014, 2015\)](#). The first study describes a methodology to quantify resilience of Sustainable Drainage Systems (SUDs) that combines hydraulic performance with utility performance metrics during flooding (exceedance) conditions. In their second study, this methodology is used to evaluate the performance of an urban drainage system when subjected to a range of structural failure scenarios resulting from random cumulative link failures. Through detailed modelling of the SUDs, the study concludes that capital investments are insufficient to enhance resilience, unless they are combined with asset management strategies such as cleaning and maintenance.

Finally, some workgroups and conferences give consideration to resilience infrastructure either by studying the effect of acute stressors or resilience challenges. From WEFTEC 2015, [Goldbloom-Helzner et al. \(2015\)](#) has developed a guide to identify flood resilience vulnerabilities in the United States based on real flooding experiences, and [Wood et al. \(2015\)](#) analyses the interventions that San Francisco's combined sewer system needs to implement in

order to cope with climate change. From conference proceedings in the AIWW 2015, [Schellekens and Ballard \(2015\)](#) present a new planning methodology to improve financing of resilience projects that takes into account stakeholders involvement early in the project.

4. Analysis of the reviewed academic studies

A comprehensive analysis of the 17 reviewed academic studies was conducted, covering stressors evaluated, system properties analysed, metrics (i.e. the different methodologies, equations and scenario analysis) and interventions proposed to implement resilience.

The low number of papers matching the characteristics of the search is relevant in itself. A recent analysis of the use of resilience as a concept in literature ([Hosseini et al., 2016](#)), showed that the engineering sector is a late adopter of the term, compared to environmental, ecology and psychology sectors; and it is within engineering fields such as oil, gas and nuclear that resilience assessment has become common practice ([OREDA, 2009](#)).

4.1. Stressors assessed

All case studies assess a particular system under one or more stressors. As has been indicated in [Fig. 3c](#), chronic stressors are far more commonly studied than acute, with eighteen studies giving

consideration to them. Detailed information on the studies and the stressors they assess can be found in [Table 1](#). The most common stressor is WRRF influent variation, including storm water. In second place chronic equipment failures (including infrastructure ageing) and urban changes. In third place, concern is also given to increase in water use and climate change. Other stressors mentioned are run-off, stringent legislation and public perception. On the other hand, only five studies considered acute stressors. The most common acute stressor is flooding, although it can be considered chronic in certain regions of the world such as England. Other acute stressors assessed in literature are: cold weather event, storm event, power outage, short-term drought and wildfire ([Schoen et al., 2015](#)); the WERF report ([Gay and Sinha, 2013](#)) also mentions hurricanes, severe thunderstorms, blizzards, and tornadoes. All the studies can serve as a set of examples for similar case studies. However, a methodology should be used to systematically characterize stressors in a way that can be used in models, such as the one proposed in [Cuppens et al. \(2012\)](#).

The number and type of stressors studied to date is still a small subset of all the possible stressors that can affect wastewater infrastructure. Furthermore, perhaps due to the predominance of physical models, the range of stressors includes mainly those of physical nature. Regards have been given to compliance and public perception ([Weirich et al., 2015](#)), but only from a scenario analysis point of view, there is no methodology to include them in the metrics analysis yet.

4.2. Properties of a resilient system

As shown in [Table 2](#), the most commonly studied properties were rapidity (12 out of 17 academic studies), followed by robustness (11) and flexibility (7). All the other qualities such as connectivity and redundancy were considered in less than 3 studies, and 4 qualities only are defined by [Butler et al. \(2014\)](#) and not applied to a case study. When this list is compared to system properties or performance associated with resilience in other fields (e.g. urban resilience), three properties are still missing: *reflective* understood as using past experience to inform future decisions. *Inclusive*, in the sense of social action, such as prioritize broad consultation to create a sense of shared ownership in decision making. And lastly, *integrated*: a system that brings together a range of distinct systems and institutions. The 'reflective' property is addressed indirectly by [Butler et al. \(2016\)](#), who identify 'learning' as an important step in increasing resilience. System properties considered in urban resilience studies typically have a broader scope ([IWA Guidelines for water wise cities, 2016](#)), which may be attributed to the inclusion of social and political stressors.

[Fig. 2](#) identifies the relationship between the variables of the system that can be related to properties that make the system resilient. Current literature only covers a small set of properties, with fewer studies covering multiple properties. The system properties and/or performance attributed to resilience, their definitions and scope, varied depending on the project. This has been observed not only in the wastewater field, but throughout the whole engineering sector ([Hosseini et al., 2016](#)). Consensus on these subjects is the cornerstone of resilience assessment benchmarking. Although not every study has to include all the potential properties and performance measures, it is good practice to specify which ones will be covered. Studies such as Infrastructure system reliability and vulnerability assessments, are currently conducted without reference to resilience. The integration of properties and performance contributing to resilience into a standard framework, will allow all the studies to be linked in a holistic assessment.

4.3. Metrics

12 studies have developed a methodology to calculate resilience, either with qualitative or quantitative metrics. In the reviewed studies, qualitative assessments tend to be "top to bottom"; they start big, and then draw conclusions on the small components. Quantitative assessment, on the other hand, has required in-depth knowledge and characterisation of the different parts of the system under study.

4.3.1. Qualitative

There are 3 studies dealing with qualitative metrics. [Butler et al. \(2014\)](#) proposes an assessment that is intended to be descriptive, by means of a study of the properties and performance of a resilient system. In this framework, further developed by [Butler et al. \(2016\)](#), four types of resilience analysis are considered: Top-down, Middle-based, Bottom-up and Circular. These approaches are classified and recommended based upon the following elements: emerging threats, intervening water system, system performance, and social, economic, and environmental consequences. In the third study, [Schoen et al. \(2015\)](#) actually uses both qualitative and quantitative assessments. The qualitative part of the study is carried out by evaluating the critical functions of the system for the following properties: robustness, adaptive capacity/redundancy, rapidity, and resourcefulness, against the following short-term events: (1) extreme cold-weather event; (2) storm event; (3) power outage; (4) widespread wildfire; (5) drought; and long term (climate change): (6) temperature increases; (7) changes in precipitation; and (8) sea level rise. The quantitative part of the study will be analysed in the next section.

4.3.2. Quantitative

All the studies proposing a metric, including the previous 3 studies in the qualitative section, also considered a quantitative measurement of resilience. The quantitative approach typically consists of linking the properties of the system to its performance, which is done by monitoring system variables affected by stressors. The most common system variables used to measure the performance of the system are: effluent quality/pollution units, level of service, energy consumption and monetary loss. This may result into a mathematical equation that assigns a value to resilience, although often the equation is not provided and the analysis is done by direct comparison of results between scenarios. Thus, depending on the case study, specifically the properties considered, the variables monitored and the level of detail needed, the resulting approach might be very different. Nevertheless, these studies have three clear points in common: they contain a model of the system; develop a range of possible scenarios, and one or several state variables are monitored to serve as indicators of system performance. Scenarios can be created randomly, using Monte-Carlo (MC) techniques, arbitrarily, or deliberately, using a consistent methodology from literature such as [Lempert et al. \(2015\)](#).

[Cuppens et al. \(2012\)](#) puts an emphasis on stressors. It proposes a methodology to identify and generate the stressors, characterise and monitor them. Resilience is then calculated through the modelling of the system after the affected processes of the plant are studied, and their dynamics modelled under a range of scenarios. Metrics which contribute to resilience assessment are loss of functionality (considered a measure of robustness), and recovery time (rapidity). This approach can be expressed mathematically in [Eq. \(1\)](#), which has in turn been illustrated in [Fig. 4](#). It has been adapted and put into practice by 6 studies in the literature review.

Table 2
Overview of the properties found in the current resilience literature, and the studies including them.

Property	Definition	Studies
Robustness or absorptive	Ability to reduce severity of unexpected perturbation and to maintain its function operating in dynamic conditions	Cuppens et al., 2012; Francis and Bekera, 2014; Hwang et al., 2014; Mugume et al., 2014, 2015; Ning et al., 2013; Schoen et al., 2015; Weirich et al., 2015; Xue et al., 2015; Scott et al., 2012; Sweetapple et al., 2016
Rapidity or recovery	Time to recover from a perturbation to the previous steady state.	Cuppens et al., 2012; Francis and Bekera, 2014; Hwang et al., 2014; Mabrouk et al., 2010; Mugume et al., 2014, 2015; Ning et al., 2013; Schoen et al., 2015; Weirich et al., 2015; Xue et al., 2015; Scott et al., 2012; Sweetapple et al., 2016
Flexibility or adaptive	Accommodate changes within or around the system; and establish response behaviours aimed at building robustness and recovery	Butler et al., 2014; Francis and Bekera, 2014; Gersonius et al., 2013; Hopkins et al., 2001; Ning et al., 2013; Schoen et al., 2015; Weirich et al., 2015
Connectivity	Degree of interconnectedness or duplication	Butler et al., 2014, 2016; Francis and Bekera, 2014
Redundancy	Degree of overlapping function in a system	Butler et al., 2014, 2016; Cuppens et al., 2012; Francis and Bekera, 2014
Homeostasis	Effective transmission of feedbacks between component parts	Butler et al., 2014
Omnivory or resourceful	Diversifying resource requirements and their means of delivery.	Butler et al., 2014; Cuppens et al., 2012; Schoen et al., 2015
High Flux	High availability of resources through a system	Butler et al., 2014
Flatness	Avoiding hierarchical systems to adjust behaviour quicker in front of sudden perturbances	Butler et al., 2014
Buffering	Design with studied excess capacity	Butler et al., 2014

$$Res = \int_{t_0}^{t_n} (M_0 - M_t) dt \quad (1)$$

where t_n is the total duration of the perturbation until recovery; t_0 is the initial time when the perturbation occurs; M_0 is the initial state of the chosen metric (a state variable representative of the state of the system) and M_t is the value of the chosen metric at a measured time t .

This methodology has been applied to the whole range of scales, from reactor to UWWs. Francis and Bekera (2014) builds on this system and includes also the adaptive capacity; the study assesses resilience of any system above reactor level, using an equation that considers 3 properties: absorptive (robustness), adaptive and restorative (rapidity). This is done by giving consideration to the profile of the recovery curve through a set of parameters shown in Eq. (2).

$$Res = \rho_i = S_p * \frac{F_r * F_d}{F_o} \quad (2)$$

where S_p is the speed recovery factor, F_o the original stable system performance level, F_d the performance level immediately post-disruption, and F_r the performance at a new stable level after recovery efforts have been exhausted.

At WRRF level, Sweetapple et al. (2016) uses this methodology (Eq. (1)) to evaluate the trade-off between resilience and reliability by means of a virtual case study. Two resilience indicators, $R_{deficit}$ and $R_{duration,max}$, are used, based on performance deficit and maximum performance failure duration respectively under a range of disturbance magnitudes. These are calculated as follows:

$$R_{deficit} = \sum_{k=0}^1 \frac{\sum_{i=1}^N (T_i - E_i)}{\sum_{i=1}^N T_i} \quad (3)$$

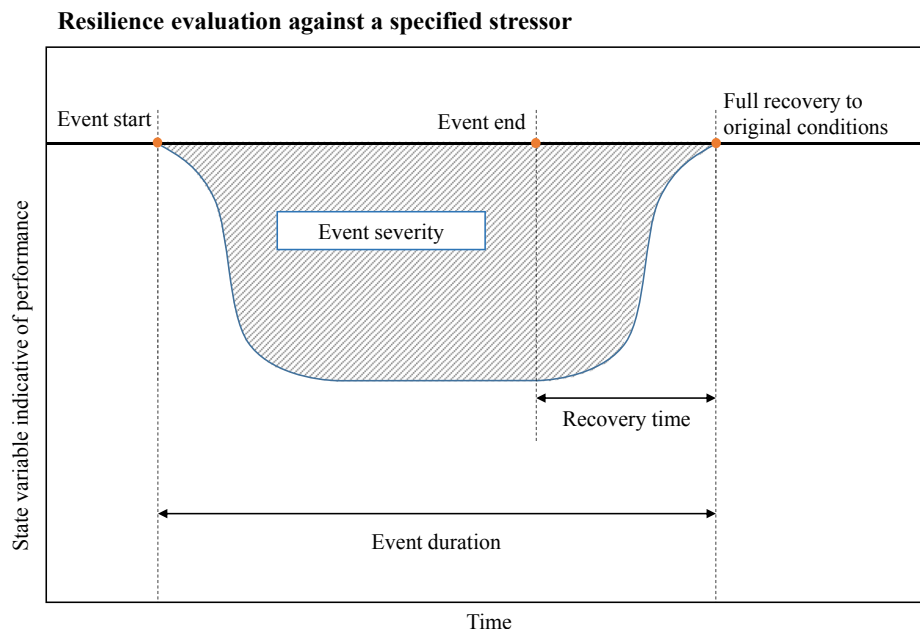


Fig. 4. Graphical representation of assessment of resilience to a stressor. Adapted from Mugume et al. (2015).

$$R_{duration,max} = \sum_{k=0}^1 \frac{T_{total} - \max_{k=1..M}(F_k)}{T_{total}} \quad (4)$$

where k is the normalised disturbance magnitude, N the number of time steps, T_i the threshold at time step i , E_i the threshold exceedance at time step i , T_{total} the total duration of the evaluation period, F_k the duration of failure event k , and M the number of times failure state is entered.

The novelty of their approach is the use of multiobjective optimisation to assess the cost-function of an intervention to build resilience, and further evaluation by means of multiobjective visualization tools. This approach can be extrapolated to balance the cost/value between resilience implementation with other objectives in a project, such as reliability in this case.

Ning et al. (2013) use the approach in Fig. 4 to calculate the resilience of an urban wastewater system, with a focus on urban drainage, against long-term changes of chronic stressors. Resilience is calculated by the Storm Water Management Model (SWMM) and empirical models based on land-use to monitor pollution levels under a range of future urban development scenarios. Two metrics are used: environmental carrying capacity (ECC) and the ordinary pollution emission (OPE). The advantage of this approach is that allows to calculate severity on account of a specific threshold. In other words, the measurement of resilience (R_v) depends on the capacity of the receiving waters to sustain pollution (OPE - ECC). The implementation is shown in Eq. (5).

$$R_v = \frac{(O_{in} + D_{in}) - In^{ECC}}{DL} < 0, \text{ If } OPE - ECC > 0,$$

$$R_v = 0, \text{ If } OPE - ECC = 0, \quad (5)$$

$$R_v = \sqrt{\frac{(DP_{in}^* DR_{in}^*)}{DL^2}} > 0, \text{ If } OPE - ECC < 0,$$

where OPE is the ordinary pollution emission; O_{in} is the quantity of the ordinary influent caused by the residential population; D_{in} is the quantity of the disturbance influent caused by the floating population and urban runoff; In^{ECC} is the quantity of virtual wastewater that contains the threshold amount of pollutants to achieve the maximum requirement of the environmental constraint; DL refers to the designed load of a WRRF; DP_{in}^* and DR_{in}^* represent the maximum quantity of domestic wastewater and urban runoff, respectively.

Also on sustainable urban drainage systems (SUDS), Mugume et al. (2014) applies this methodology (Fig. 4.) using as the main indicators flood intensity and duration. The model is a combination of a linked network and the previous SWMM. In a second study (Mugume et al., 2015), the model is run across a range of scenarios to benchmark interventions for SUDS resilience to floods. At a smaller scale, Mabrouk et al. (2010) applies this it at reactor level; using a dynamical model obtained by deriving the mass balances of biomass and pollution. The objective is to show the effect of small chronic stressors (e.g. influent variability) on the rapidity (property) of a reactor, and how it affects the optimum design parameters. Finally, Schoen et al. (2015) used it for a resilience assessment focused on technology benchmarking of an urban wastewater system. The qualitative analysis is complemented with a qualitative model (Eq. (6)); the equation draws two profiles: a failure-profile accounting for robustness and redundancy, and a recovery profile accounting for resourcefulness and rapidity. Unlike the previous cases, this model also considers the lifespan of the

infrastructure.

$$\text{Resilience (RI)} = \sum_j (T_i + F_j \Delta T_f + R_j \Delta T_r) / \text{lifespan} \quad (6)$$

where j is the challenge index, T_i is the time to the incident, F is the failure profile, ΔT_f is the duration of the failure, R is the recovery profile and ΔT_r is the duration of the recovery.

The main drawback of the approach presented in Fig. 4, is that it requires a physical characterisation and accurate knowledge of the process dynamics of the system. An alternative to this method is statistical modelling.

Weirich et al. (2015) used a statistical approach based on a Generalized Linear Model (GLM) for predictive modelling of WRRF performance. It uses pollutant concentrations in the effluent as indicators and 10-year long series scenarios. A second example of a statistical approach is Hwang et al. (2014), this time using a linear programming (LP) model. The LP model computes the resilience of a water supply system in different case scenarios, such as decentralized versus centralized wastewater treatment. Although these models do not have the level of detail of an in-depth, white-box model, this approach can be used for first-pass simulation purposes, mainly at planning level.

Overall, the key insights that could be drawn on to increase the understanding in the wastewater sector are: first, the “linking properties to performance” approach is limited, in the sense that it cannot take into account non-physical variables of the system that cannot be directly measured, such as public involvement. In this area, complementary qualitative approaches are necessary. Secondly, different levels of model detail should be used depending on the project. At planning level, statistical models are more appropriate, whereas at small scale, physical models provide better understanding and prediction power, at the expense of increased data requirements and calibration costs.

4.4. Proposed interventions to increase resilience

As can be seen in many of the studies that presented a practical case study, a resilience assessment not only focuses on assessing the overall resilience of the system qualities, but also benchmarking its current state against interventions that can potentially increase resilience. This point of view is also directly stated in the WERF foundation report: Water Infrastructure Asset Management Primer (Gay and Sinha, 2013). A classification of the interventions found in the literature have been presented in Table 3.

The most common measure is buffering (extra capacity), straightforward and widely used, particularly when dealing with variable WRRF influent (the most common stressor). On second place, equipment back-up and asset renewal, which are directly related with equipment failures (second most common stressor). Other interventions include increased repair strategy, active asset management and asset protection. The first one is also related to equipment failures, the second one concern long-term changes (such as the third most common stressor: climate change); and the last one concerns protection against acute stressors (catastrophic events) such as flooding. Finally, energy production is also mentioned in one study.

As with the properties discussed in the current literature, the interventions proposed focus on technical aspects. Changes in the behavioural, social or governance paradigms are rarely considered, and only if the previous interventions did not work. Social education towards water reuse for example, plays a vital role in budget constraints (Hering et al., 2013).

A key point is that an intervention that contributes positively to one property of resilience may impact negatively on another

Table 3
Summary of interventions to enhance resilience found in current literature.

Measure	Type	Description	References
Buffering. Storm water tanks	Natural risks	Adequately planned overcapacity and storm tanks for extra storage	Currie et al., 2014; Mabrouk et al., 2010; Mugume et al., 2015; Technical reports
Spare replacement equipment and back-up	Mechanical failures	overlapping in key equipment, storage of spare parts	Currie et al., 2014; Mugume et al., 2015; Technical reports
Asset renewal	Mechanical failures	Removal of old, and installation of new equipment.	Currie et al., 2014; Schoen et al., 2015; Technical reports
Active asset management	Preventive maintenance	Sensors and real time control, multiobjective optimisation	Butler et al., 2014; Sweetapple et al., 2016; Technical reports
Centralized/decentralized	Planning	Centralize/decentralize a system when appropriate depending on the system's needs.	Butler et al., 2014; Hwang et al., 2014; Schoen et al., 2015
Assets protection	Natural risk (climate change and floods)	Proofing critical assets from natural risks by means of hardened infrastructure, barriers and water-proofing pumps.	Currie et al., 2014; Technical reports
Increased repair strategy	Mechanical failures	Identifying the most sensitive equipment and increasing its checking/calibration times	Currie et al., 2014; Technical reports
Energy production	Planning	Cogeneration facilities and other energy interventions	Butler et al., 2014

(Sweetapple et al., 2016). In order to test the effectiveness of interventions, these have to be assessed holistically against a range of properties and scenarios of stressors. As an example, automated control and storm tanks increase system's robustness and rapidity, but active control requires higher maintenance costs and trained staff requirements, which create an added vulnerability. In facilities lacking qualified personal or with high energy prices, it may not be the best solution. On the other hand, having active control entails data gathering which might enhance reflectivity (learning from past experiences) and resourcefulness (e.g. flexible catchment permitting).

5. Future research directions

The use of resilience as a sustainability concept in wastewater systems management is at an early age. Academia, industry and government agencies need to work together for a successful implementation. Based on the outcomes of this review and the mentioned reports from US and UK water organisations, the following research directions have been identified to help the research community and the professionals working in resilience of urban wastewater systems. Each category falls under one element of resilience assessment.

5.1. A comprehensive lens of system stressors

The current literature review considers stressors in areas such as: natural risk, mechanical failures, and planning. However, this is still a small subset of the whole range of stressors the wastewater sector will be facing in the future. Climate change is likely to affect wastewater treatment in several ways and the underlying climate variability is anticipated to increase (Milly et al., 2008). Flooding is also expected to increase in future (Campos and Darch, 2015a), prolonged periods of dry weather will lead to sedimentation in sewerage systems, followed by increased 'first flush' pollutant loads (Campos and Darch, 2015b). More treatment may be required if consents are tightened to reflect changes in environmental flows. Mechanical failures and preventive planning are rarely considered in water management, and neither are trends within the systems such as wearing or reduced efficiency. The challenge is to develop a comprehensive study of stressors affecting wastewater treatment, to understand all the potential vulnerabilities.

A special case is that of the unknown stressors, unpredicted stressors that have profound effects on the performance of a WRRF during its lifetime (Dominguez, 2008). For known stressors, the challenge is to properly combine available tools (e.g. influent generators, sewage pattern generators, reliable WRRF models and cost models) to economically evaluate alternatives in the operation/design/upgrade. However, in order to deal with extreme uncertainty, instead of adapting the system for one stressor, a qualitative assessment to enhance the system properties is more appropriate. Complementary approaches include using adaptive planning techniques such a scenario analysis, and flexible managerial perspectives.

5.2. Common framework for resilience properties and assessment

The main challenge in resilience assessment is to have a framework that manages resilience effectively, making possible the comparison between cases. Resilience should be defined as a change in our philosophy to assess and prevent risk. This way, the need for standardization is combined with the need for being flexible, namely, an appropriate methodology for each study. Having a common definition that reflects all properties would constrain resilience assessment, since each case has specific necessities and thus will assess different properties. Each system is different and therefore different solutions are necessary, whereas a unique methodology would limit the effectiveness of the solutions. A framework should act as a guideline that: a) contains a study of possible stressors, b) summarizes different methodologies, sets of properties, tools, metrics and cases study, c) includes interventions to increase resilience to be benchmarked. This would help companies to adapt their assessments to the requirements of the project. Hitherto, only Butler et al. (2016) has considered different types of interventions of resilience assessment under the same framework.

Complementary, wastewater systems are still part of a bigger picture, where they integrate with other urban resources. A functional framework should not only understand and manage resilience as asset based, but also provide feedback to broader frameworks (i.e. Infrastructure Asset Management (IAM) frameworks).

5.3. A comprehensive lens of system metrics, and how to measure them

As stated in the analysis section, in order to take into account the whole set of properties of a resilient system it is necessary to use both qualitative and quantitative assessment. The challenge is on developing a set of metrics that link to all the properties, and create an algorithm or equation to monitor and measure them. The set of metrics should include alternatives for each property, and also account for different scales, and levels of detail depending on the goals of the study. To date, there is no clear method to link non-physical properties to the performance of the system. Qualitative assessment has a key role in incorporating economic, social, legal and governmental variables into the assessment.

There are a number of tools available that have already been used in the studies included in the literature review, such as deterministic or probabilistic modelling techniques, influent generators, adaptive planning techniques, Monte Carlo analysis, sensitivity analysis, multi-objective optimisation, and sets of stressors and measures, to mention but a few. The challenge is to reorient these tools to resilience assessment, taking into account resilience metrics and quantitative algorithms. A second challenge will be choosing state variables for monitoring the performance; we need to identify which variables are representatives of the system's state, and develop efficient technology and procedures to monitor them. The third challenge resides on the integration of academic tools into practice.

5.4. Interventions to increase resilience: investment is both the main barrier and driver to resilience planning

The level of acceptable resilience in the system is determined not only by the needs identified in a resilience assessment, but also by the cost-assessment of the interventions. Investment in wastewater infrastructure is one of the biggest challenges for the water sector. Therefore, the uncertainty on the cost-assessment will be decisive in the decision making, and potentially the main barrier to resilience implementation.

However, water industries should not see investing in resilience as an extra cost, but as a means to encourage further investment by other stakeholders. By understanding the resilience of the plan, we understand the risk profiles, which might attract new investment opportunities. Resilience financing needs to be involved in the project as early as possible (Schellekens and Ballard, 2015). The challenge is to design a framework to appropriately benchmark and demonstrate the effectiveness of interventions. This will unlock new investment opportunities, whereas not understanding resilience will be the actual barrier to the investment.

6. Conclusion

This work has conducted a critical review of studies that deal with resilience in the wastewater treatment sector, with a special focus on understanding how they addressed the key elements for assessing resilience. Four key elements have been identified in a resilience assessment: stressors, properties, metrics and interventions. The results of the review showed that:

- Only 17 peer-reviewed papers and 6 relevant reports, a very small subset of the work in wastewater research, explicitly addressed resilience.
- The lack of consensus in the definition of resilience, and the elements of a resilient assessment, is hindering the implementation of interventions to build resilience in wastewater management.

- No framework for resilience assessment is complete, comprehensive or directly applicable to practitioners. Current frameworks are lacking some key elements such as: a comprehensive study of stressors, properties and metrics, examples of cases study, and the ability to benchmark interventions or connectivity with broader frameworks.
- Increasing resilience is generally seen as an additional cost or extra effort, instead of a means to overcome project uncertainty that would unlock new opportunities of investment.
- The existing tools have to be brought to practice and further developed from a resilience implementation perspective in order to be effective.

This paper defines possible research directions in order for resilience theory to be implemented and support the wastewater industry to face future challenges. Firstly, resilience research in the wastewater needs to improve consensus and coordination. A key issue is to obtain a working framework for resilience assessment that is connected to broader asset management plans. Secondly, resilience needs to be understood as a means to unlock investment and handle uncertainty. Thirdly, existing tools need to be reframed under the resilience perspective, and new studies linked into the bigger resilience picture.

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